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Greenhouse Gas Emissions From a Community Anaerobic Digester with Mixed Organic Wastes

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***Abstract**. Opportunities for reducing greenhouse gas (GHG) emissions through farm manure management systems and the implementation of anaerobic digestion are of growing interest to farmers, electric utilities, and environmentalists alike. There is a prevalent concern however, that, certain elements of centralized anaerobic digestion (e.g. transportation) constitute emissions additional to current manure management systems. This thesis attempts to shed light on this dilemma by developing a scenario modeling methodology to project potential GHG emissions from five potential anaerobic digestion systems that have been proposed by the Cornell University Department of Biological and Environmental Engineering and the Department of Applied Economics and Management in the context of an economic feasibility study completed for the Town of Lowville, New York, and the County of Lewis, New York. The proposed Lewis County community digester is presented as an example of community-based co-digestion of mixed organic wastes and its implications for GHG emission reductions accounting within an economic feasibility framework.*

The research findings reinforce that anaerobic co-digestion of manure and food processing waste can considerably soften the carbon footprint of dairy production at the community scale. Expanding transportation networks do indeed lessen the net emission reductions of anaerobic digestion projects *in which biomass transportation is considerable. However, on the scale of this analysis, emissions associated with transportation were relatively inconsequential to the overall balance of GHGs.*

Keywords. Agriculture, agricultural management, agricultural wastes, anaerobic digesters, anaerobic digestion, analysis, biogas, cattle manure, climate change, environmental impact, manure management, scenario modeling, dairy, codigestion, co-digestion, mixed wastes, organic waste.

I. Introduction

Opportunities for reducing greenhouse gas (GHG) emissions through farm manure management systems and the implementation of anaerobic digestion are of growing interest to farmers, electric utilities, and environmentalists alike. There is a prevalent concern however, that, certain elements of centralized anaerobic digestion (e.g. transportation) constitute emissions additional to current manure management systems. This thesis attempts to shed light on this dilemma by developing a scenario modeling methodology to project potential GHG emissions from five potential anaerobic digestion systems that have been proposed by the Department of Biological and Environmental Engineering and the Department of Applied Economics and Management in the context of an economic feasibility study.

The thesis provides an introduction to the issue and contextual information about anaerobic digestion and climate change. It then articulates the methodologies of community assessment, information gathering, experiment design, and scenario modeling. The results of research conducted using these methodologies are then presented and the thesis concludes with a discussion of these results.

II. Greenhouse gas emissions and anaerobic digestion

U.S. greenhouse gas emissions rose 17 percent between 1990 and 2007 (EPA 2009). Agriculture as a sector was responsible for emissions of 413.1 teragrams of CO_2 equivalents (Tg CO_2e), or 6 percent of total U.S. GHG emissions (EPA 2009). Anthropogenic emissions resulting from agriculture are primarily methane (CH_4) and nitrous oxide (N_2O) — gases with global warming potentials of 21 times and 310 times that of carbon dioxide[1] (EPA 2009, EPA 2005 - a). The animal livestock sector contributes significantly to overall U.S. GHG emissions, placing a premium on emissions reduction strategies that can provide added benefits to farmers (Koneswaran and Nierenberg 2008). Enteric (intestinal) fermentation and manure management contributed 24 and 8 percent of total methane emissions, respectively, with dairy and beef cattle responsible for a larger share of this debt than any other domestic animal type, contributing more than twice as much to agricultural GHG emissions than manure management, which accounts for 7 percent of total anthropogenic methane emissions and 4 percent of nitrous oxide emissions in the U.S. (EPA 2009 and Pitesky et al. 2009).

Anaerobic digestion provides a unique point of entry to address greenhouse gas emission reduction in agriculture while simultaneously producing added benefits for community stakeholders. As a source of combined heat and power, digesters can offset the consumption of fossil fuels, resulting in indirect emission reductions beyond direct changes to manure management systems. The addition of substrates has been shown to significantly boost biogas production, multiplying this effect (Gooch et al. 2007, Morin et al. 2010, Pronto et al. 2009). Poor manure management can be a source of nitrogen runoff — a serious problem for freshwater ecosystems — and can be addressed in part with anaerobic digestion (Hjort-Gregersen 2005).

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[1] EPA defines the global warming potential of a greenhouse gas as “the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas,” with the reference gas in this case being carbon dioxide (2009, 2005 - a).

Manure management can potentially contribute further to both methane and nitrous oxide emissions, making dairy a significant source of U.S. greenhouse gas emissions. While GHG emissions per unit of milk produced have decreased throughout the second half of the 20th century, livestock and dairy production still make up a significant contribution to agriculture's carbon footprint (Capper et al. 2009).

Digesters reduce GHG emissions partially by capturing methane and nitrous oxide that would otherwise be emitted to the atmosphere under traditional manure management practices, while some — namely anaerobic —storage systems contribute little if at all to emissions (CCAR 2008). These emissions can be substantial — liquid manure management systems alone, which have become increasingly popular, have contributed to a 44.7% increase in methane emissions from manure management since 1990 (EPA 2009, Steinfeld and Wassenaar 2007).

In the case of co-digestion, food wastes and other inputs (called substrates) are diverted from landfills, where they would otherwise add to greenhouse gas emissions. Landfills accounted for 23% of all U.S. methane emissions in 2008 (EPA 2009). Additionally, processed waste is of significantly less weight (40%) and volume than in raw form, contributing to reductions in odor typically welcomed by dairy communities (Ostrem 2004).[2]

This farm-based approach to tackling interrelated environmental problems (greenhouse gas emissions, nitrogen runoff, nutrient imbalance) is consistent with an "ecoagriculture" approach as defined by Scherr and McNeely (2008), in which agricultural productivity is reconciled with production-dependent rural livelihoods and healthy ecosystems. GHG emission reduction targets could be met in part by agricultural practices, and through the sale of carbon credits, farmers stand to benefit economically from change in such practices. In the rural areas of developing countries, digesters are becoming a prolific solution electricity-access problems with added environmental benefits (Tsai and Lin 2009, Yu et al. 2008).

Presently, few uniform standards exist to account for emissions reductions due to anaerobic digestion — those that exist are not consistently or universally applied (Pronto et al. 2009). Since the emission reduction potential of a particular project could influence its economic feasibility in a carbon-based economy, emission quantification plays an increasingly important role in digester-system design.

The proposed Lewis County community digester is presented as an example of community-based co-digestion and its implications for greenhouse gas emissions reduction accounting in an economic feasibility framework.

Note: This work was done as an extension of a larger technical and economic feasibility study "Feasibility Study of Anaerobic Digestion and Biogas Utilization Options for the Proposed Lewis County Community Digester Project," completed March 2010 by Curt Gooch, Jennifer Pronto, Brent Gloy, Norm Scott, Steve McGlynn, and Chris Bentley. Any references to a "feasibility study" refer to this report.

III. Research question and approach

[2] The first anaerobic digester in the U.S. was installed at a swine farm in Iowa during the 1970s with the express purpose of reducing odor (Saffterman and Triponi 2008).

Within the foregoing context, this research was designed to examine the tradeoffs associated with economic efficiency and greenhouse gas emission reduction in community scale anaerobic digestion systems. Specifically, it employs a scenario modeling approach to assess whether the most economical system design is also the greatest emissions reducer. We anticipated that the findings might generate useful insight into the larger issue of manure management as a means of reducing the carbon footprint of the livestock sector.

IV. Methodology

Several steps of data acquisition were involved in the research described below. First, data on farm and community biomass availability were determined through surveys. Then, samples of non-farm biomass were collected from identified contributors and analyzed for biomethane production potential. Finally, the resulting data were used as a basis for greenhouse gas emission reduction estimations made through the scenario modeling framework described below.

Data Acquisition

Farm and Community Biomass Survey

In order to determine the concerns of local dairy farmers, industry, and residents, two surveys were developed by Cornell University's Manure Management Program, Cornell Cooperative Extension of Lewis County, the Town of Lowville Economic Development Office and local volunteers.

CCE Representatives administered farm-based surveys by mail in Fall 2008. To improve response rate, the farm-based surveys were administered face-to-face in Spring-Summer 2009. Town of Lowville officials and volunteers administered non-farm surveys face-to-face in Spring-Summer 2009.

Two different surveys were developed and subsequently administered by the project. The first was a survey of farms within 20 miles of Lowville in any direction to determine the usable quantity of manure. The second was a non-farm survey given to local businesses to determine the nature and volume of food waste and off-farm inputs.

The notable difference between the farm and non-farm survey information is that the non-farm data specified the basic composition of each respondent's waste. The respondents were asked whether or not they currently pay for removal of such waste in order to determine their likeliness to cooperate in a community project. (A full report from 7/15/2009 substrate sampling is available in the appendix.)

In total, 25 non-sand bedded farms were surveyed, with 14 farms producing at least 3,000 gallons of manure per day. Non-farm survey data was collected from 10 organic waste producers, varying from very small contributions of grass and flower clippings to large volumes of whey and dairy waste.

Biochemical Methane Potential Testing (BMP trials)

Six community food waste samples (2, 4, 5A, 5B, 8, 10) were analyzed for biochemical methane potential (BMP) by Rodrigo Labatut at the Cornell Agricultural Waste Management Laboratory. All samples were analyzed in triplicate, with the exception of substrate 4, which was analyzed with 6 replicates, due to the high variability of the substrate samples, resulting in seven individual BMP trials.

The lab procedures for conducing BMP trials are listed below (Labatut and Scott 2008):

- *320-mL bottles are used in the trials, and contain 200 mL of substrate, inoculum, and nutrient medium. Inoculum is an active anaerobic mixed culture media obtained from an operating bench scale AD reactor. The nutrient medium is added for the purpose of providing the necessary nutrients and trace elements for the microorganism to thrive.*
- *Bottles with only inoculum were used in the set up as controls, to account for the background methane produced in the bottles by the inoculum.*
- *Bottles containing only water were also used in the set up as controls, to correct for internal pressure variations due to external temperature and atmospheric pressure fluctuations.*
- *Prior to incubation, bottles were gassed-out with a mixture of 70% N_2 and 30% CO_2 and sealed immediately.*
- *Sealed bottles were placed in a mesophilic (37±1°C) incubator containing a shaker to constantly agitate the bottles during the trials.*
- *The biogas production within the bottles was determined by pressure transducers attached to a hypodermic needle inserted through the septa of each bottle.*
- *Pressure measurements were performed continuously over a period of 30 days using a data acquisition (DAQ) system connected to a computer.*
- *Pressure data recorded by the DAQ system were converted to volume of biogas at a standard temperature and pressure (STP) according to the ideal law of gases ($PV = nRT$).*
- *Temperature inside the incubator was also continuously monitored through the DAQ with a thermocouple placed inside a control bottle containing water.*
- *Methane and carbon dioxide content in the biogas was determined by a gas chromatograph (GC) and the methane yield was subsequently calculated.*

Transportation

Transportation costs are typically the largest operating cost of a community-scale anaerobic digestion process — in several cases, they have been prohibitively high (Bothi and Aldrich 2005, Bennett 2003, Jewell et al. 1997, Edgar and Hashimoto 1991).

As part of the feasibility study, it was determined that either a project-owned and -operated trucking fleet, or an existing local contractor could be used. A particular local contractor operates a fleet of 6,500-7,000 gallon trucks — this contractor served as a model for fuel consumption estimates and transportation capacity. A transportation methodology was developed that considered time required to pump and load/unload such trucks, as well as the proximity of participating farms to the digester(s). Projected trucking schedules were developed by members of the feasibility study team to account for the transportation of scenario-specific biomass loads at maximum economic efficiency.

Estimating GHG Emissions

Scenario Modeling

Since the Lewis County Community Digester has not yet been constructed, no metering or direct measurement could be conducted to assess the greenhouse gas impact of the project. Instead, projected biogas production and potential biomass trucking routes (as mentioned) were used to estimate prospective greenhouse gas emissions. It is recognized that there can be significant differences between modeled GHG emission reductions and actual emission reductions, typically resulting in a smaller amount of methane actually captured and destroyed upon operation than in the modeled case. In order to minimize this potential shortfall, when a range was given for potential emission reductions, the conservative value was used. In the absence of metered data, this analysis makes extensive use of emission factors from various sources — emission factors incorporate a great deal of uncertainty and should be considered rough (Bhattacharya et al. 2000).

Four scenarios were developed in exploration of a feasible system design. They are listed below:

1. One centralized digester located adjacent to the Lowville Wastewater Treatment Plant, receiving manure from *all* surveyed farms and select food wastes.
2. One centralized digester located adjacent to the Lowville Wastewater Treatment Plant, receiving manure from *select* surveyed farms and select food wastes.
3. Two decentralized, regional digesters — one located about 8 miles north of Lowville (Site 1) and one located about 8 miles south of Lowville (Site 2) — receiving manure from select farms and select food wastes.
    a. Two decentralized, regional digesters — one located about 8 miles north of Lowville (Site 1) and one located about 8 miles south of Lowville (Site 2) — receiving manure from select farms and select food wastes, with *partial volumes* of manure *transported by pipe.*
4. Two decentralized, regional digesters — one located about 8 miles north of Lowville (Site 1) and one located about 8 miles south of Lowville (Site 2) — receiving manure from select farms, select food wastes, *and energy crops*. Energy crop 1 would be co-digested at site 1, and energy crop 2 would be co-digested at site 2.

As defined in the USEPA Climate Leaders Protocol (2006), the emissions accounting boundary includes direct emissions of CH_4 and N_2O associated with manure management processes, emissions that result from the electricity used for blower or heater, and from the transportation of materials directly associated with anaerobic digestion[3]. While CCAR (2008) notably excludes N_2O emissions from its accounting boundary due to a “conservatism factor”, this methodology includes estimates of nitrogenous emission reductions to more completely reflect changes in manure management processes.

A project can produce offsetting effects outside of the physical limits of the anaerobic digester itself that affect the net greenhouse gas impact of the project. Transportation, in this case, includes not only the transportation of manure and food waste influent to the digester, but also the transportation of digester effluent back to the farm.

Since they would not have occurred with the advent of the digester project, emissions associated with leakage are included. Equipment used for land application is not included in the physical boundary for the assessment, since on-farm hauling and transportation practices are not expected to change significantly due to the digester’s

[3]Emissions of CO_2 from manure are not included because the manure is from biogenic sources — namely as crops in livestock feed — so subsequent emissions do not add to the atmospheric concentration (Pertl et al. 2010, EPA 2006).

construction (see Fig. X below for a visual representation of the accounting boundary). Likewise, emissions associated with land application are not included within the project boundary as they are not expected to change significantly. It is possible that by producing an effluent with a lower viscosity than manure, anaerobic digestion could encourage more long-distance pumping of fertilizer. However, this is not anticipated to have a significant impact on emissions.

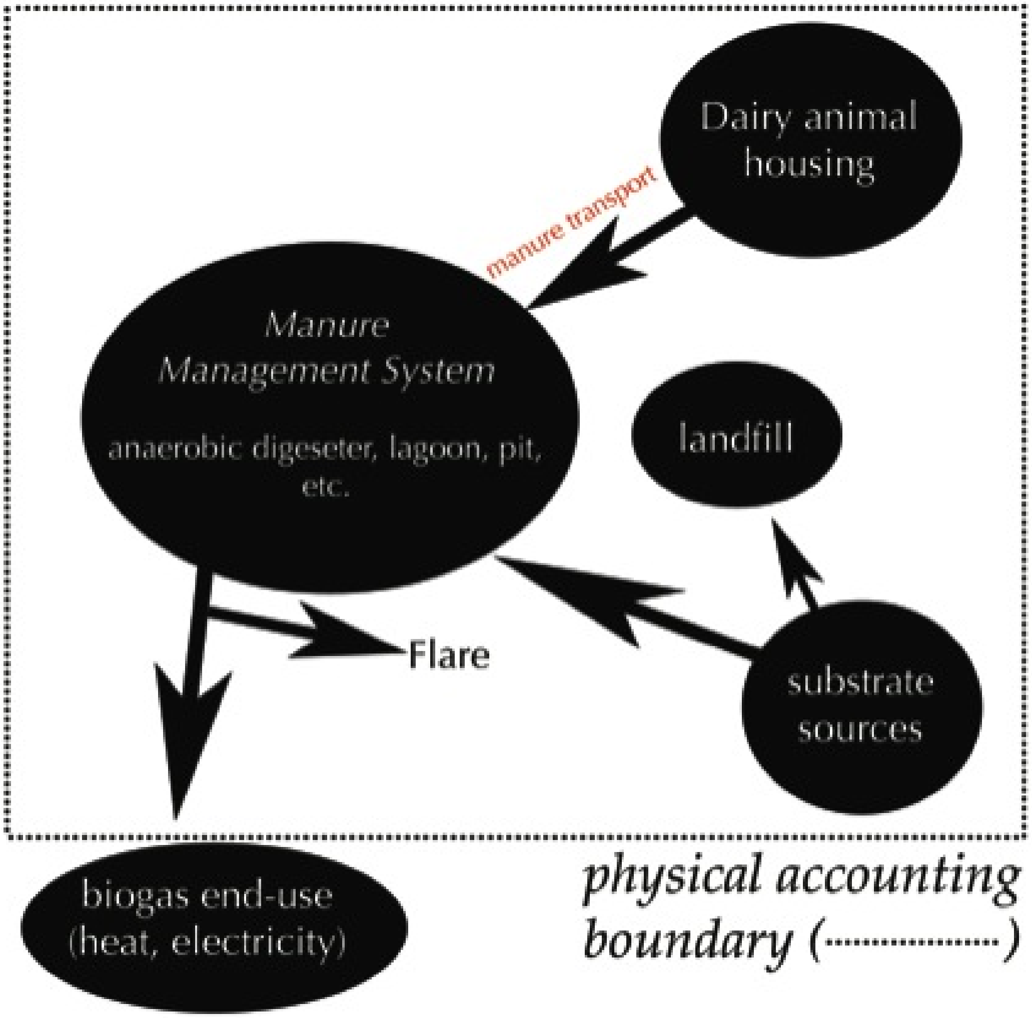

Figure 1. The physical accounting boundary.

The underlying methodological concept was derived from accounting principles developed by the IPCC (2006) and EPA (2006). A baseline scenario was established by estimating emissions resulting from the manure management systems currently in place. The baseline scenario was one in which, in the absence of any project-related activity, manure and food waste are left to decay, emitting greenhouse gases into the atmosphere.

Then, the same factors were used to project greenhouse gas emissions for the operation of the digester(s). Leakage from the digester(s) is incorporated into the emissions estimates in the form of methane capture efficiency. Emissions resulting from transportation were added to the total emissions in each scenario.

Anaerobic digestion can contribute to the generation of renewable energy, if the methane produced during digestion is combusted for electrical generation. However, GHG emission reductions associated with displacing grid-delivered electrical energy are considered an indirect emission, and are thus not included in the emission reduction estimates. As CCAR Protocol (2008) points out, only direct emission reductions due to GHG capture and abatement within the physical boundaries of the project can be claimed — capturing and using methane to produce electricity for the grid is a separate GHG reduction project. Further, since the future of the Lewis County digester is unclear, it is not necessarily the case that the electricity generated will be delivered to the grid.

Most emission reduction accounting methodologies emphasize additionality — reductions that are above and beyond the business-as-usual scenario (CCX 2009, CCAR 2008, EPA 2006). The project emissions were subtracted from the baseline emission scenario (business-as-usual) to determine the greenhouse gas reductions of the project.

$$\text{Emissions reductions} = \text{Emissions}_{BASELINE} - \text{Emissions}_{PROJECT}$$

Throughout the report, annual numbers are given to best account for seasonal fluctuations where applicable. Furthermore, where a range of values was presented in the survey data or in the feasibility study, the conservative end value was used unless otherwise noted.

The following values were used:

- The biogas generated at the digester(s) is 60% CH_4 by volume.
- Since the proposed digester(s) will be enclosed (not covered anaerobic lagoons), biogas capture efficiency was assumed to be 95% — an average of the IPCC's (2006) conservative 90% efficiency and EPA's (2008) 99%. An additional 0.25% of leakage was assumed for scenario 3a to account for leaky pipelines and shut-off devices (Pertl et al. 2010).
- Trucks transporting manure and food waste were assumed to get 5 miles per gallon of diesel fuel[4]. The combustion of diesel fuel was assumed to produce 22.912 lbs of CO_2e / gal (Wightman 2008).
- The global warming potential of CH_4 was assumed to be 25 that of CO_2; the global warming potential of N_2O was assumed to be 310 that of CO_2 (IPCC 2007).

Baseline Scenario

CH_4 Emissions$_{BASELINE}$ = (lbs VS/day) / (2.2 kg / lb) x (365 days / year) x (0.662 kg CH_4/m^3 CH_4) x (GWP_{CH4}) x (.25 m^3 CH_4/kg VS) x [emission factor] = kg CO_2e / year

[4] Figure based off fuel efficiency for 6,500-7,000 gallon tankers reported by a local contractor in Lewis County.

To estimate baseline emissions, a methane conversion factor of .17 was used to represent the liquid/slurry manure management system currently in place at the surveyed farms (IPCC 2006, EPA 2008)[5]. An emission factor of .05 is used for each anaerobic digester in the scenario analyses (EPA 2008, EPA 2006, IPCC 2006).

N_2O $\text{Emissions}_{\text{BASELINE}}$ = (lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28)[6] x (GWP_{N2O}) x [emission factor] = kg CO_2e / year

For N_2O baseline emissions, a global warming potential of 310 was used (EPA 2005 – a). An emission factor of 0.005 was used to represent the liquid/slurry manure management system currently in place at the surveyed farms (IPCC, 2006 and EPA, 2008). An emission factor of 0 is used for each anaerobic digester in the scenario analyses (EPA, 2006).

Manure emissions

All manure management systems produce GHG emissions (EPA, 2006). However, emissions vary with manure management practices as well as time and temperature. Currently, no farms in the Lowville area store manure in a covered anaerobic lagoon — while such storages exist, they are not common in the Northeast. Instead, liquid/slurry manure management systems prevail. The cohort thus has important implications for dairy GHG emission reductions statewide — liquid/slurry manure storage accounts for 47% of NY State dairy manure methane emissions, more than any other manure management practice (Wightman, 2006).

The surveyed farms employ a liquid/slurry system for storage and spread the contents for use as a soil amendment and organic fertilizer as needed. Farms with storage specifically for solid manure[7] were not surveyed on the basis that it would be too hard to transport solid manure to the digester. Since the few farms using solid manure are spreading daily, it would also represent a significant change in the behavior of these farmers to participate in the digester project.

EPA (2009) provides methane conversion factors for manure management systems. Liquid/slurry systems are considered to be 17% effective in capturing methane, while digesters are given a default value of 90%. However, specific values for plug-flow digesters of reasonable technical efficiency are assigned a capture efficiency of 99% — as mentioned earlier, a compromise of 95% was assumed for this analysis. N_2O emission factors are also given: 0.005 for liquid/slurry; 0 for anaerobic digestion.

Manure emissions will vary by scenario according to the contributions of farms not participating in each scenario. Manure from these farms is assumed to remain under a liquid/slurry management system, emitting CH_4 and N_2O according to EPA (2009) default factors.

$\text{Emissions}_{\text{MANURE}} = \text{Emissions}_{\text{PROJECT, MANURE}} + \text{Emissions}_{\text{NP FARMSs}}$

[5] Lewis County's mean annual temperature is 43.8°F, placing it in the "cool" climate for IPCC and EPA emission factors (Lowville Weather Station).
[6] Conversion factor, N_2O –N to N_2O (EPA 2006).
[7] Manure is largely liquid in nature, with a solid portion that can be separated off through treatment. Only one farm in Lewis County has such equipment.

Transportation emissions

$Emissions_{TRANSPORT}$ = (miles annually) / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 kg per lb = kg CO_2e / year

In keeping with the prominent GHG accounting methodologies, emissions associated with additional transportation specifically associated with the anaerobic digestion project were considered to be within the physical accounting boundary (Wightman 2008, EPA 2006, IPCC 2006).

Since the feasibility study was completed with a specific local contracting service in mind, their fuel efficiency value of five miles per gallon of diesel was used. As identified by Wightman (2008), the Regional Greenhouse Gas Initiative's (RGGI) value of 22.912 lbs CO_2 per gallon of diesel was used.

Substrate emissions

Climate Action Reserve's (2009) *Organic Waste Digestion Project Protocol* was used as a model to account for GHG emission reductions associated with the diversion of the identified substrates from disposal to anaerobic digestion. The protocol provides a first order decay model for calculating baseline methane emissions from landfilled food waste streams (Equation 5.4).

Substrates 1,3,6,7, and 9 make up only about 55 MT of waste annually in aggregate, and are thus negligible when considered against the sources likely to be used (2,4,5A, 5B, 8, 10, and 11), which total to 60,000-78,000 MT annually.

Values of both the fraction of total degradable organic carbon (by weight) in each food waste stream and the fraction of the degradable organic carbon that decomposes under anaerobic conditions differ between food waste and post-digested sludge, both of which are present in each scenario. The respective values for each substrate are applied to the proportion of the total substrate input that the substrate represents.

A global warming potential[8] of 25 is used for methane instead of CAR's recommended 21, in order to maintain consistency with the rest of our report's estimations and with the most recent IPCC guidelines (2007). Decay rates are differentiated by climate, with Lewis County qualifying as wet temperate.

Finally, the fraction of methane captured and destroyed under anaerobic digestion is assumed to be 95%, in keeping with previous efficiency estimates within the report. In the case of the baseline scenario, the CAR default 75% is used; for scenario 3a, 94.75% is used to account for additional leakage in the pipeline and associated equipment.

Construction emissions

[8] "The global warming potential (GWP) of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas." The reference gas used is CO_2. All gases are subsequently presented in units of CO_2 equivalents. (EPA, 2009)

Presently, no methodology exists to explicitly quantify emissions associated with the construction of anaerobic digestion systems. In the place of such an approach, data from EPA's Sector Strategies Division report, *Quantifying Greenhouse Gases in Key Industrial Sectors of the U.S.* (2008) is used. The default emission factor of 0.37 $MTCO_2e/_{2002}\$1000$[9] for construction projects associated with "Water and sewer line and related structures construction" was determined to be the best estimate for construction of (an) anaerobic digestion system.

In the absence of estimations regarding the capital costs of construction in each scenario, data from an analogous project were used — Jewell et. al's (1997) analysis of community-scale anaerobic digestion was on the same scale (128,000 tons manure / year; 4,700 cows) as plans for the Lewis County digester (145,000 tons manure / year; 5,000 cows). The capital cost of this project — $_{1997}\$1,550,000$ was adjusted for inflation according to data from the *Statistical Abstracts of the United States* to obtain a value of $_{2002}\$1,739,843$.

$$\text{Emissions}_{\text{CONSTRUCTION}} = \$1,739,843 \times 0.37\ MTCO_2e/\ \$1000 = 643.74\ MTCO_2e$$

The resulting value of 644 $MTCO_2e$ was added to the project emissions in each scenario.

Seven participating farms (5, 11, 14, 16, 19, 21, and 23)[10] would need on-farm, short-term storages conducted in order to facilitate biomass transportation associated with the project. The feasibility study estimated the cost of a sufficient facility to be \$28,750 (\$24,248 in 2002 dollars). To estimate emissions from this construction, EPA's (2008) standards for "poured concrete foundation and structure contractors": 0.24 $MTCO_2e/_{2002}\$1000$.

As an alternate method, default standards for construction of "nonresidential manufacturing structures" provided by Carnegie Mellon University's Environmental Input-Output Life Cycle Analyses were applied to the capital cost of the digester (Carnegie Mellon University Green Design Institute 2010). The resulting 761 $MTCO_2e$ could be considered an alternate value for construction emissions of the project.

Flare

In most anaerobic digestion systems, a flare is used to burn excess biogas. The resulting CO_2 would be considered an additional anthropogenic source of GHG emissions associated with the project. However, it is expected that one large local client's electricity demand will make full use of the output from the digester. Therefore, minimal flare use is anticipated should any scenario be adopted. Especially considering

[9] The unit "$_{2002}\$$" denotes the value U.S. dollars in 2002, as compared to current values of inflation. Likewise, "$_{1997}\$$" signifies U.S. dollars as valued in 1997.
[10] Scenario 1 included all of these farms; scenario 2 included all but 16 and 19; scenarios 3, 3a, and 4 included all but 5 and 16.

the 96% default efficiency of flares (CCAR 2008), potential emissions from flare use are considered negligible in this analysis.

Offsetting onsite electricity use

EPA (2008) distinguishes electricity produced for use onsite from electricity produced for sale to the grid in terms of GHG emission reductions. As mentioned earlier, the production of energy for use offsite is considered a separate project, so emission reductions due to the offset of fossil fuel-based electricity are considered indirect and not within the physical accounting boundary.

Although some heat and electricity may be used to satisfy the demands of the engine-generator set onsite, this parasitic energy requirement does not represent any additional emissions of GHGs as it remains within the closed loop of the anaerobic digestion project system — no baseline scenario energy demand is satisfied by the provision of such heat or electricity. Furthermore, CAR (2009) considers biogas used as a replacement fuel for onsite equipment as a complementary and separate activity. There is no subsequent effect on project GHG emission reductions.

Additionally, energy use associated with existing manure management systems (i.e. transport of manure to and from storage on-farm, spreading) is assumed not to change significantly with the advent of anaerobic digestion in any scenario, as on-farm transport will remain essentially the same.

Estimates of emission reductions due to displaced electricity were made, however, and are included in a secondary emission reduction estimate. These estimates were made using New York State energy portfolio emission factors (EIA 2010). The emission factor (0.3455 kg CO_2e), which was designed to reflect the fuel mix of New York State's energy portfolio, was multiplied by the projected electrical energy value of manure calculated for each scenario. Since the future of the Lewis County digester is unclear, it is not necessarily the case that the electricity generated will be delivered to the grid. Values are nonetheless given for consideration:

Scenario 1: 0.3455 kg CO_2e x 9,858,901 = 3,406,250 kg CO_2e / yr offset

Scenario 2: 0.3455 kg CO_2e x 7,905,088 = 3,004,327 kg CO_2e / yr offset

Scenario 3: 0.3455 kg CO_2e x 8,179, 138 = 3,108,481 kg CO_2e / yr offset

Scenario 3a: 0.3455 kg CO_2e x 8,179,138 = 3,108,481 kg CO_2e / yr offset

Scenario 4: 0.3455 kg CO_2e x 8,179,138 = 3,108,481 kg CO_2e / yr offset

V. Results

This section details results from the farm survey first. Additional considerations for the codigestion of energy crops (originally unanticipated) are then presented before results from the community biomass survey. Likewise, additional considerations for the codigestion of food waste from nearby military reservation Fort Drum, NY are presented next. The results of the biomethane production potential trials are presented next. The last of the base data presented pertains to the transportation requirements of each scenario. Finally, emissions reductions are tabulated for each scenario according to the accounting methodology above.

Farm Survey

A summary of the data obtained through the farm survey is shown in Table 1 (*See Appendix*). Using information provided in the American Society of Agricultural and Biological Engineers (ASABE) Engineering Practices Standard (ASABE, 2005) along with information from the farm survey reports, estimates were made of the daily mass of manure production and composition farm by farm.

In order to account for the fact that dry cows and heifers produce less manure and volatile solids and per day than lactating cows, the manure quantity and composition produced by each animal management group was expressed on a lactating cow equivalent ($LCE_{TS\ basis}$) on a total solids basis. This unit uses ASABE standards for the total solids produced per cow per day to adjust for the reduced production of manure from heifers.

Information regarding existing manure storage, road access, and bedding type is included in Table 1. Storage, access, and bedding are all items needed to help determine the degree to which a farm would be able to participate in a community digester project. Farms with a lack of nutrients, for example, would likely be interested in the nutrient-rich effluent produced as a byproduct of anaerobic digestion.

a. Quantity: low number of cows prompted investigation of alternative sources of manure

Although the continuous collection of completed surveys continued throughout the beginning of the study period, there was initial concern about the low number of cows (and subsequently low volume of manure) to potentially supply the anaerobic digester. This led to an expansion of the search, namely to include sand-bedded farms.

Alternative Biomass Sources — Energy Crops

The possibility of growing energy crops for anaerobic digestion was also considered. Lewis County has few strictly crop farms, comprising approximately 2,400 total acres. Assuming 19 tons per acre of production, this amounts to a potential for approximately 296,000,000 ft^3 of biogas each year. A summary of these calculations is presented in Table 2.

Table 2. Energy crop potential.

Crop farm #	Farm acreage	Crops grown (acreage)	Distance from Lowville
1	2,000	Corn (1,000), grass (500), alfalfa (500)	15 miles north of center
2	350	Corn (150), alfalfa grass (200)	12 miles south of center

Alternative Biomass Sources — Fallow Ground

Finally, the possibility of digesting several hundred acres' worth of reed canary grass that grow along the Black and Beaver Rivers in Lewis County was considered. Historically, this acreage has been harvested for bedding hay. This option was ultimately rejected, especially considering the logistical difficulties the fragmented ownership of the property posed. Furthermore, spring flooding along the Black and Beaver rivers typically leaves a large amount of sediment and debris in the fields. A summary of the challenges presented by this biomass source is presented below:

- Accessible acreage will vary from year to year based on weather conditions. Acreage was significant in 2008 and 2009 previously inaccessible for harvest until late August-early September due to wet conditions.
    - Some of this land is not conducive to large equipment due to the water table and spongy nature of the soils.
  - There is a great deal of debris at harvest due to the frequent flooding.
  - Even in dryer years harvesting at a time conducive to fermenting a crop can be a challenge.
  - Attempts to establish any crop other than the native reed canarygrass have had very limited success
  - Very fragmented parcels with many landowners — could present logistical challenges in terms of coordinating landowners to unify in an effort to establish a meaningful acreage of this land that would be consistent from year to year.

b. Perspective: willingness to cooperate heavily dependent on benefits to farmer

While it was ultimately decided that those farmers who took the time to fill out a survey could be considered interested or cooperative simply because of their decision to participate in the survey, most of the farmers responded to the "perspective questions" with caution. "If it benefits me," was a common reply of the respondents' willingness to give up their manure. Delivery of the nutrient-rich effluent will likely prove to be an important determinant of the project's ultimate success.

Non-Farm Survey

Many of the proposed inputs were unusable, including bones from a butcher, napkins, and coffee grounds. A considerable education and/or waste separation project is needed if further food waste contributions from the community are sought.

A summary of the results from the non-farm survey data is presented in Table 2 (*See Appendix*).

Alternative Biomass Sources — Fort Drum

As with the farm survey results, an initially low quantity reported prompted the investigation of alternative sources. This included Fort Drum, the large military base north of Lowville — it was discovered that Fort Drum intends to develop their own waste management system to deal with the food waste from their centralized dining facilities on their own.

Residential food waste was also considered as a possible input, but serious investigation was postponed in light of the difficulties inherent in such large organizational undertakings and the unlikelihood of developing a representative sample of such a variable waste stream.

Sample Analysis

Biogas calculations

The average biogas production potential for all substrates and manure is 146 million ft^3 per year.

The two substrates with the most meaningful quantities of biogas production were 8 and 10. 2 and 11 were the second highest producers. The whey was discovered to be very diluted, which accounts for the low methane yields, and the sludge from Kraft has already undergone a digestion process, which accounts for the low methane yields from that substrate.

The impact on gas production from the substrates is very small in relation to manure, not due to methane yields of the substrates, but due to the sheer volume available when compared with the almost 35,000,000 gallons of manure produced each year.

Transportation

It was determined that the local contractor option was more economically feasible than the startup fleet. A summary of relevant data from this portion of study is provided in Table 3.

Table 3. Biomass transport data.

Scenario #	Annual miles (trucking influent and effluent)	Annual costs
1	144,646	$1,383,940
2	118,653	$1,202,500
3	68,727	$647,830
3a	65,606	$483,990
4	65,606	$483,990*

**Since energy crops will be grown at farms near regional digesters, there is no considerable increase in trucking miles.*

Greenhouse gas emissions estimates

Direct emission reductions

A summary of the calculations for each scenario, as described in the methodology section, is presented below. Total emission reduction estimates are given in kilograms of CO_2 equivalent per year. Two values are given for the project scenarios: one representing just direct reductions associated with changes in manure management practices ("manure"), and one including estimated reductions from landfill diversion ("total"). The difference is displayed on the line between these values as the estimated emission reductions due to substrate landfill avoidance.

Baseline Scenario

CH_4 Emissions$_{BASELINE,}$ = (90,620 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 10,575,019.32 kg CO_2e / year

N_2O Emissions$_{BASELINE}$ = (5,227 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x [.005] = 2,112,268 kg CO_2e / year

- *A sample calculation is given below for modified EPA (2009) estimations of organic waste diversion, as described in Methodology:*

  CH_4 Emissions$_{baseline,\ food\ waste}$ = weight (MT) × [.9 x DOCf x MCFlf x GWP x (.9) x (16/12) x .5] ×TDOC ×(1−e−^{k})×∑ e^{-k} ×(1−LCEx)

  60,000 MT x .9 x [(.84 x .683) + (.5 x .317)] x .9 x 25 x .9 x1.333 x .5 x [(.137 x .683)+(.05 x .317)] x .169 x 3.137

  = 30,957,254 kg CO_2e / yr

CH_4 Emissions$_{BASELINE,\ SUBSTRATES}$ = 30,957,254 kg CO_2e/yr

Emissions$_{BASELINE,\ MANURE}$ = 12,687,287 kg CO_2e / year

Emissions$_{BASELINE,\ W/SUBSTRATES}$ = 43,644,541 kg CO_2e/year

Scenario 1

In scenario 1, manure from the 25 surveyed non-sand bedded farms and select food wastes (the 7 non-farm biomass substrates with the highest volumes: 2, 4, 5A, 5B, 8, 10, 11) would be transported to the digester by truck.

CH_4 Emissions$_{SCENARIO\ 1}$ = (90,620 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 3,110,300 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 1}$= (5,227 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.005 = 0 kg CO_2e / year

Emissions$_{TRANSPORT}$ = 144,646 miles annually / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 = 301,284 kg CO_2e / year

- *Project manure emissions was added to manure emissions from non-participating (NP) farms (in this case the value is zero, since all farms are included in scenario 1):*

CH_4 Emissions$_{SCENARIO\ 1,\ NP}$ = (0 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 0 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 1,\ NP}$ = (0 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.05 = 0 kg CO_2e / year

Emissions$_{CONSTRUCTION}$ = $1,739,843 x 0.37 MT$CO_2$e / $1000 = 643.74 MT$CO_2$e = 643,740 kg CO_2e

+ 7 ($24,248) x 0.24 MT$CO_2$e/$_{2002}$$1000 = 40.737 MT CO_2e = 40,737 kg CO_2e

Emissions$_{SCENARIO\ 1}$ = 4,055,584 kg CO_2e / year

Emissions reductions$_{SCENARIO\ 1,\ MANURE}$ = 9,576,988 kg CO_2e / year

Emission reductions$_{SUBSTRATES,\ SCENARIO\ 1}$ = 4,863,161 kg CO_2e/yr

Emissions reductions$_{SCENARIO\ 1,\ TOTAL}$ = 13,454,387 kg CO_2e / year

Scenario 2[11]

In scenario 2, the same central digester would receive manure from only 14 of the surveyed farms — those producing at least 3,000 gallons of manure daily — and select food wastes (the 3 non-farm biomass substrates with the highest volumes: 8, 10, and 11).

CH_4 Emissions$_{SCENARIO\ 2}$ = (72,550 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 2,490,093 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 2}$ = (4,225 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

Emissions$_{TRANSPORT}$ = 118,653 miles annually / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 = 247,143 kg CO_2e / year

CH_4 Emissions$_{SCENARIO\ 2,\ NP}$ = (147,945 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 2,108,702 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 2,\ NP}$ = (1,002 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.05 = 404,915.36 kg CO_2e / year

[11] *Note:* Scenario 2 is presented here as originally developed; after considering input from stakeholders in Lowville, the feasibility study team altered scenario 2 for the final publication of that document.

$Emissions_{CONSTRUCTION}$ = \$1,739,843 x 0.37 $MTCO_2e$ / \$1000 = 643.74 $MTCO_2e$ = 643,740 kg CO_2e

+ 5 (\$24,248) x 0.24 $MTCO_2e/_{2002}$\$1000 = 29.098 MT CO_2e = 29,098 kg CO_2e

$Emissions_{SCENARIO\ 2}$ = 5,894,854 kg CO_2e / year

Emissions $reductions_{SCENARIO\ 2,\ MANURE}$ = 7,683,576 kg CO_2e / year

Emission $reductions_{SUBSTRATES,\ SCENARIO\ 2}$ = 4,884,915 kg CO_2e/yr

Emissions $reductions_{SCENARIO\ 2,\ TOTAL}$ = 11,648,510 kg CO_2e / year

Scenario 3

In scenario 3, two regional digesters (here, D1 and D2) would receive manure from select surveyed farms and select food wastes. D1 would receive manure from 12 of the surveyed farms, while D2 would receive manure from four of the surveyed farms. These farms were chosen for their proximity to their respective digesters. D1 would co-digest substrate number 8, which is the highest volume non-farm biomass substrate that is nearest D1. Site 2 would co-digest substrate numbers 10 and 11, which are the highest volume non-farm biomass substrates nearest D2.

CH_4 $Emissions_{SCENARIO\ 3,\ D1}$ = (42,417 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 1,455,855 kg CO_2e / year

CH_4 $Emissions_{SCENARIO\ 3,\ D2}$ = (23,297 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 671,672 kg CO_2e / year

N_2O $Emissions_{SCENARIO\ 3,\ D1}$ = (2,471 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

N_2O $Emissions_{SCENARIO\ 3,\ D2}$ = (1,356 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

$Emissions_{TRANSPORT}$ = 68,727 miles annually / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 = 143,152 kg CO_2e / year

CH_4 $Emissions_{SCENARIO\ 3,\ NP}$ = (17,594,095 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 5,625,112 kg CO_2e / year

N_2O $Emissions_{SCENARIO\ 3,\ NP}$ = (1,400 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.05 = 565,750 kg CO_2e / year

$Emissions_{CONSTRUCTION}$ = \$1,739,843 x 0.37 $MTCO_2e$ / \$1000 = 643.74 $MTCO_2e$ = 643,740 kg CO_2e

+ 5 (\$24,248) x 0.24 $MTCO_2e/_{2002}$\$1000 = 29.098 MT CO_2e = 29,098 kg CO_2e

$Emissions_{SCENARIO\ 3}$ = 8,433,869 kg CO_2e / year

Emissions reductions$_{\text{SCENARIO 3, MANURE}}$ = 5,040,570 kg CO_2e / year

Emission reductions$_{\text{SUBSTRATES, SCENARIO 3}}$ = 4,884,915 kg CO_2e/yr

- *Substrate emissions in scenarios 3, 3a, and 4 were identical to those of scenario 2, as the same substrates are being digested, without the addition of any additional capture and destruction of methane.*

Emissions reductions$_{\text{SCENARIO 3, TOTAL}}$ = 9,109,495 kg CO_2e / year

Scenario 3a

Scenario 3a is identical to scenario 3, except that partial volumes of the manure would be transported to the digester by pipe instead of truck. At D1, five of the 12 participating farms would send their manure to the digester by pipe. At D2, two of the four participating farms would send their manure to the digester by pipe.

CH_4 Emissions$_{\text{SCENARIO 3A, D1}}$ = (42,417 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .0525 = 1,528,648 kg CO_2e / year

CH_4 Emissions$_{\text{SCENARIO 3A, D2}}$ = (23,297 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .0525 = 705,255 kg CO_2e / year

N_2O Emissions$_{\text{SCENARIO 3A, D1}}$ = (2,471 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

N_2O Emissions$_{\text{SCENARIO 3A, D2}}$ = (1,356 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

Emissions$_{\text{TRANSPORT}}$ = 65,606 miles annually / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 = 136,651 kg CO_2e / year

CH_4 Emissions$_{\text{SCENARIO 3A, NP}}$ = (17,594,095 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 5,625,112 kg CO_2e / year

N_2O Emissions$_{\text{SCENARIO 3A, NP}}$ = (1,400 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.05 = 565,750 kg CO_2e / year

Emissions$_{\text{CONSTRUCTION}}$ = $1,739,843 x 0.37 $MTCO_2$e / $1000 = 643.74 $MTCO_2$e = 643,740 kg CO_2e

+ 5 ($24,248) x 0.24 $MTCO_2$e/$_{2002}$$1000 = 29.098 MT CO_2e = 29,098 kg CO_2e

Emissions$_{\text{SCENARIO 3A}}$ = 8,500,161 kg CO_2e / year

Emissions reductions$_{\text{SCENARIO 3A, MANURE}}$ = 4,967,777 kg CO_2e / year

Emission reductions$_{\text{SUBSTRATES, SCENARIO 3A}}$ = 4,884,915 kg CO_2e/yr

Emissions reductions$_{\text{SCENARIO 3A, TOTAL}}$ = 9,043,203 kg CO_2e / year

Scenario 4

Scenario 4 is identical to scenario 3, except that energy crops are included in the analysis. The same farms and non-farm biomass substrates would be used to provide material to each of the digesters. Energy crop 1 would be digested at D1, while energy crop 2 would be co-digested at D2.

CH_4 Emissions$_{SCENARIO\ 4,\ D1}$ = (42,417 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 1,455,855 kg CO_2e / year

CH_4 Emissions$_{SCENARIO\ 4,\ D2}$ = (23,297 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .05 = 671,672 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 4,\ D1}$ = (2,471 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 4,\ D2}$ = (1,356 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0 = 0 kg CO_2e / year

Emissions$_{TRANSPORT}$ = 65,606 miles annually / 5 miles per gallon x (22.912 lbs CO_2e / gallon) / 2.2 = 136,651 kg CO_2e / year

CH_4 Emissions$_{SCENARIO\ 4,\ NP}$ = (17,594,095 lbs VS/day) / (2.2 kg/lb) x (365 days/year) x (.25 m^3/kg VS) x (0.662 kg CH_4/m^3 CH_4) x (25) x .17 = 5,625,112 kg CO_2e / year

N_2O Emissions$_{SCENARIO\ 4,\ NP}$ = (1,400 lbs N/day) / (2.2kg / lb) x (365 days / year) x (44/28) x (310) x 0.05 = 565,750 kg CO_2e / year

Emissions$_{CONSTRUCTION}$ = \$1,739,843 x 0.37 MTCO_2e / \$1000 = 643.74 MTCO_2e = 643,740 kg CO_2e

+ 5 (\$24,248) x 0.24 MTCO_2e/$_{2002}$\$1000 = 29.098 MT CO_2e = 29,098 kg CO_2e

Emissions$_{SCENARIO\ 4}$ = 8,427,368 kg CO_2e / year

Emissions reductions$_{SCENARIO\ 4,\ MANURE}$ = 5,040,570 kg CO_2e / year

Emission reductions$_{SUBSTRATES,\ SCENARIO\ 4}$ = 4,884,915 kg CO_2e/yr

Emissions reductions$_{SCENARIO\ 4,\ TOTAL}$ = 9,115,995 kg CO_2e / year

Table 4. Annual electricity value and emissions reductions.

Scenario #	Annual electrical energy value*	Emissions reductions MANURE	Emissions reductions SUBSTRATES
Baseline	\$0	0 kg CO_2e/yr	0 kg CO_2e/yr
1	\$943,578	9,576,988 kg CO_2e/yr	13,454,387 kg CO_2e/yr

2	$777,760	7,683,576 kg CO_2e/yr	11,648,510 kg CO_2e/yr
3	$787,529	5,040,570 kg CO_2e/yr	9,109,495 kg CO_2e/yr
3a	$787,529	4,967,777 kg CO_2e/yr	9,043,203 kg CO_2e/yr
4	$1,652,112	5,040,570 kg CO_2e/yr	9,115,995 kg CO_2e/yr

**Assuming an industrial average retail price of $0.871 / kWh (EIA 2009).*

VI. Discussion

Baseline emissions from current manure management practices were estimated at approximately 12,700 MT CO_2e / year, which equates to about 2,300 passenger vehicles on the road each year (EPA, 2005). The dairy farming community represented by this scenario is within a 15-mile radius of one rural town — it is telling that its business-as-usual GHG emissions simply from manure management practices could be orders of magnitude greater than the farmers contribution from personal transportation each year.

After reviewing the feasibility study interim report data, the Lowville Digester Work Group decided to pursue scenario 2 for the conclusion of the feasibility study, with modifications to include the co-digestion of energy crops. Technical concerns were cited[12], but minimizing the economic impact of trucking fees was paramount to the decision. Indeed, at $82 / hour, trucking fees quickly make biomass transport economically infeasible. Interestingly, though, GHG emissions associated with transportation only amounted to about 7% of total emissions (without substrates) at most (Table 5). Transportation emissions were indeed highest (both in absolute and relative terms) for scenario 1, which displayed the greatest emission reductions (both with and without substrates). However, they played a relatively small role in the GHG emission assessment of the scenarios. **Table 5. Transportation emissions as a portion of total emissions.**

Scenario #	Transportation emissions [kg CO_2e / yr]	Total emissions (without substrates) [kg CO_2e / yr]	Transportation emissions as % of total
1	301,284	4,096,061	7.36
2	247,143	5,923,692	4.17
3	143,152	8,462,707	1.69
3a	136,651	8,528,999	1.60
4	136,651	8,456,206	1.62

[12] The 3,000-gallon minimum limited the likelihood of manure freezing — a logistical advantage over scenario 1, in which all surveyed farms were included. Further, less risk was associated with a single, centralized digester. Should a few farms be unable to contribute as planned, the overall impact on influent reduction would be proportionately less than with multiple, decentralized sites.

Methane made up a large portion of the emissions in each scenario. Even though emissions resulting from leakage were higher in the centralized scenarios, they saved overall on methane emissions because they incorporated manure from more farms, cutting back on emissions from manure left in liquid/slurry storage systems. This also saved on N_2O emissions, as the accounting methodologies surveyed and used in this report did not assume any nitrogenous emissions from anaerobic digestion. On the other hand, emissions from liquid/slurry manure application, though variable, can be significant. Scenario 1 avoids the emissions relative to the baseline scenario by precipitating a change in manure management across all 25 surveyed farms.

Table 6. Emission reductions as a proportion of total baseline emissions.

Scenario #	Emission reductions as % of baseline emissions (no substrates)	Emission reductions as % of baseline emissions (with substrates)
1	67.7	30.8
2	53.3	26.7
3	33.3	20.9
3a	32.8	20.7
4	33.4	20.9

Substrate emissions had a significant effect on the relative proportion of GHG emissions reductions represented by each scenario (Table 6). The centralized digester scenarios (1 and 2) had a significant edge over the decentralized scenarios in terms of emission reductions. The pipeline scenario (3a) did show a reduction in GHG emissions relative to the decentralized scenarios without piping, however it was quite small (<1%).

The choice of bioenergy systems may be based on how efficiently GHG emissions are reduced per unit of biomass used (Schlamadinger et al. 1997). When expressed as emissions reductions per unit influent, the results reflect the relative efficiency of each scenario (Table 7).

Table 7. Efficiency of digester scenarios as GHG reductions per unit influent.

Scenario #	Volume of influent (manure and substrates) [kg / yr]	Emissions reductions per unit influent [kg CO_2e reduced / kg waste in]
1	201,820,000	7%
2	177,270,000	7%
3	170,000,000	5%
3a	170,000,000	5%
4	190,180,000	5%

While this analysis did not explicitly consider the sale of carbon credits, the estimated emission reductions indicate a sizable potential for additional revenue. This is particularly cogent in light of the fact that the feasibility study originally recommended scenario 2, which did not represent the greatest emission reductions, at least in part to save money. An interagency working group has preliminarily valued carbon credits at \$21 / MT CO_2e[13], but policy will largely determine the future of this price (Ackerman and Stanton 2010) — pending legislation could make a federal cap-and-trade scheme possible[14]. On the basis of this factor, scenario 1 could potentially make \$201,100 (without substrates) - \$282,500 (with substrates) on the sale of carbon credits each year. Significant challenges exist in the way of transaction costs for such large-scale verification and sale of carbon credits, of course.

Economic concerns also focus largely on the system's ability to produce electricity. While the production of electricity was beyond the accounting boundary of this analysis for purely environmental purposes, the amount of biogas produced (and therefore the load of electricity possible) clearly factors heavily into the decision to recommend one scenario over another. Electricity generation is the single largest source of CO_2 emissions in the U.S., representing 39% of the total (EPA, 2009). Given a different accounting boundary, where offset electricity from the grid could be considered attributable directly to the anaerobic digester, the emissions balance would be swayed by electrical production capacity as least as much as the economic balance sheet has been. The offset of fossil fuel-based electricity by project generation represents a significant boost in total emission reductions. While this analysis does not include these reductions inside the project boundary, it should be noted that under a different methodology they may represent a significant portion of the total emission reductions.

VII. Conclusions

While the percent GHG emissions reductions of the preferred scenario (scenario 1) were not as high as Turnbull and Kamthunzi (2003) observed, a 67% reduction in CO_2e is quite significant. The anaerobic co-digestion of manure and food processing waste can considerably soften the carbon footprint of dairy production at the community scale.

Expanding transportation networks do indeed lessen the net emission reductions of anaerobic digestion projects in which biomass transportation is considerable, leading to a heftier price-tag and reduced environmental benefit (Boman and Turnbull 1997). However, on the scale of this analysis, emissions associated with transportation were relatively inconsequential to the overall balance of GHGs. This betrays an inherent tendency to downplay environmental benefits in a policy environment without adequate valuation of immaterial goods.

In the U.S., approximately 850 anaerobic digesters are used at municipal solid waste facilities, and approximately 544 are used at large wastewater treatment plants (Pew 2009). Few community-scale projects incorporate co-digestion on a meaningful

[13] Actual market prices for carbon credits today are much lower. New Carbon's Voluntary Carbon Index (2009) cites a going rate of onlys\$5.20 / MT CO_2e.
[14] Carbon credits would be guaranteed a larger market in this case, potentially putting a premium on projects able to produce a steady stream of emissions reduction credits.

scale, a practice that could glean considerable environmental and economic benefits from carbon trading schemes.

A key problem with tracking greenhouse gas emissions and issuing carbon credits remains a lack of widely accepted verification methodologies that can bridge concerns of scientific certainty and economic cost-effectiveness (Ney and Schnoor 2001). More work is needed towards a policy framework that will accurately value the environmental benefits of greenhouse gas reduction. Solidifying a methodology for projecting and estimating emissions from a community-scale anaerobic co-digestion project could increase the likelihood that such environmental assessments will be conducted and weighed alongside economic feasibility studies. Despite uncertainties surrounding the ease with which actual emissions reductions can be translated in financial gain, the proliferation of such assessments can only help promote the added benefits of anaerobic digestion.

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Appendix

Table 1. Summary of farm survey data. Farms highlighted in green have at least 1 day and 8,000 gallons of short-term storage currently available. Farms with an asterisks (*) next to their name have either gravel, stone road, or paved road access.

[*Table 1 is displayed in two parts over the next two pages.*]

				trucking / storage					biogas		production
Farm	distance from center of Lowville (miles)	number of mature cows	number of heifers	lactating cow equivalents (LCE) (total solids basis)	total manure lbs / day	total manure gal / day	long-term storage (months)	total solids lbs / day	volatile solids lbs / day	biogas produced (manure only) (cf/day)	
										Lower	Upper
#1*	2	200	150	262	39,225	4,670	6	5,230	4,446	13,337	17,871
#2	6	0	150	62	9,225	1,098	"yes"	1,230	1,046	3,137	4,203
#3	6	66	10	70	10,515	1,252	5	1,402	1,192	3,575	4,791
#4	7	105	75	136	20,363	2,424	7	2,715	2,308	6,923	9,277
#5	7	420	40	436	65,460	7,793	2	8,728	7,419	22,256	29,824
#6*	7	85	70	114	17,055	2,030	6	2,274	1,933	5,799	7,770
#7*	8	150	100	191	28,650	3,411	5	3,820	3,247	9,741	13,053
#8	8	80	80	113	16,920	2,014	6	2,256	1,918	5,753	7,709
#9	8	620	407	787	118,031	14,051	4 (heifer)	15,737	13,377	40,130	53,775
#10	9	145	115	192	28,823	3,431	6	3,843	3,267	9,800	13,132
#11	9	190	160	256	38,340	4,564	6	5,112	4,345	13,036	17,468
#12*	9	195	160	261	39,090	4,654	5 (7:10 h:mc)	5,212	4,430	13,291	17,809
#13	9	155	150	217	32,475	3,866	6	4,330	3,681	11,042	14,796
#14*	9	175	80	208	31,170	3,711	5	4,156	3,533	10,598	14,201
#15	10	70	30	82	12,345	1,470	6	1,646	1,399	4,197	5,624
#16	10	62	62	87	13,113	1,561	4	1,748	1,486	4,458	5,974
#17	11	80	70	109	16,305	1,941	12	2,174	1,848	5,544	7,429
#18*	11	500	150	562	84,225	10,027	24	11,230	9,546	28,637	38,373
#19	11	400	430	576	86,445	10,291	10	11,526	9,797	29,391	39,384
#20	12	54	36	69	10,314	1,228	6	1,375	1,169	3,507	4,699
#21	13	91	60	116	17,340	2,064	6	2,312	1,965	5,896	7,900
#22	13	91	60	116	17,340	2,064	6	2,312	1,965	5,896	7,900
#23	15	130	35	144	21,653	2,578	6	2,887	2,454	7,362	9,865
#24	15	85	20	93	13,980	1,664	6	1,864	1,584	4,753	6,369
#25	18	50	60	75	11,190	1,332	16	1,492	1,268	3,805	5,098
Candidate Farms	avg. 9	3,371	2,187	4,268	640,151	76,208	avg 6.1	74,664	63,465	190,394	255,128
SUBTOTAL	avg. 10.7	4,199	2,760	5,331	799,590	95,189	avg. 7.1	106,612	90,620	271,861	364,293
(17 sand farms)	avg. 10.4			**9,445**	**1,416,750**	**168,661**		**28,335,000**	**160,565**	**481,695**	**645,471**
(24 unsurveyed)	avg. 13			1,950	292,500	34,821		39,000	33,150	99,450	133,263
SUBTOTAL				11,395	1,709,250	203,482		28,374,000	193,715	581,145	778,734
TOTAL				**16,726**	**2,508,840**	**298,671**		**28,480,612**	**284,335**	**853,006**	**1,143,028**

									nutrient management		
biogas heat produced (manure only)		sub strates added	volatile solids in substrate	biogas produced (w/substrates)		biogas heat produced		bedding type	N	P	K
(mmBtu/day)				(cf/day)		(mmBtu/day)			lbs /	lbs /	lbs /
r (mmBtu/day)	r (mmBtu/day)	(%)	(%)	Lower	Upper	Lower	Upper		day	day	day
7	10	20	25	32,674	43,784	18	24	lded pack/shavings	259	44	44
2	2	20	25	7,684	10,297	4	6	pped hay/shavings	61	10	10
2	3	20	25	8,759	11,737	5	6	chopped hay	69	12	12
4	5	20	25	16,962	22,729	9	12	chopped hay	134	23	23
12	16	20	25	54,528	73,068	29	39	matt., hay shavings	432	74	74
3	4	20	25	14,207	19,037	8	10	chopped hay	113	19	19
5	7	20	25	23,865	31,980	13	17	matress, sawdust	189	32	32
3	4	20	25	14,094	18,886	8	10	chopped hay	112	19	19
22	29	20	25	98,319	131,748	53	71	sand, chopped hay	779	134	134
5	7	20	25	24,009	32,172	13	17	chopped hay	190	33	33
7	9	20	25	31,937	42,796	17	23	sawdust	253	43	43
7	10	20	25	32,562	43,633	18	23	sand, sawdust	258	44	44
6	8	20	25	27,052	36,249	15	19	chopped hay	214	37	50
6	8	20	25	25,965	34,793	14	19	flat hay	206	35	35
2	3	20	25	10,283	13,780	6	7	hay	81	14	14
2	3	20	25	10,923	14,637	6	8	chopped hay	87	15	15
3	4	20	25	13,582	13,582	7	7	pped hay (sawdust)	108	18	18
15	21	20	25	70,159	94,014	38	51	dust hay	556	95	95
16	21	20	25	72,009	96,492	39	52	sawdust	571	98	98
2	3	20	25	8,592	11,513	5	6	chopped hay	68	12	12
3	4	20	25	14,444	19,355	8	10	matress, hay	114	20	20
3	4	20	25	14,444	19,355	8	10	chopped hay	114	20	20
4	5	20	25	18,037	24,169	10	13	sawdust	143	25	25
3	3	20	25	11,645	15,605	6	8	sawdust	92	16	16
2	3	20	25	9,321	12,491	5	7	hay	74	13	13
102	20	25	325	466,466	625,064	251		0	3,696	635	
146	196			666,058	887,900	358	477	-	5,277	906	919
86	347	20	25	1,180,153	1,581,405	634	850	-	9,351	1,606	1,606
53	72	20	25	243,653	326,494	131	176	-	1,931	332	332
140	419			1,423,805	1,907,899	765	1,026	0	11,281	1,937	1,937
286	614			2,089,864	2,795,799	1,124	1,503		16,558	2,843	2,856

Table 2. Summary of non-farm survey data.

Substrate source	Contents as indicated in survey	Quantity indicated in survey	Estimated annual quantity range available (lbs/year)		Estimated current waste disposal costs ($/year)
			Minimum	Maximum	
1	mixed food, milk, napkins, paper plates, straws	3 cubic yds/day, Sept-June	1,009,000	1,009,000	5,000
2	mixed food, liquid, paper plates	40 gal pre/day, 225 gal post/day	790,000	805,000	19,400
3	mixed food, oil, grease	25lbs /day	9,100	9,100	4,100
4	fat, guts	800-2,000 lbs/wk Dec - Oct	17,000	72,000	
5A	mixed food,	1-5 gal pre, 5-10 post / day	13,200	37,500	4,200
5B	waste grease	1 gal/weekday, 1.5 gal/weekend day	2,200	3,750	
6	flowers, stems, petals	50lbs/wk, more in Dec, Feb, May	2,400	2,700	
7	mixed food	5 gal / 2 weeks, more in Summer	1,000	1,250	
8	whey/water	42,500 gal/day	89,200,000	129,200,000	6,555,563
9	oil	5 gal / week	2,000	2,000	2,360
	vegetables	2 gal / week	800	800	
	meat	1 gal / week	400	400	
	mixed product	5 gal / week	2,000	2,000	
10	post-digested sludge	5,037,261 gal / year	41,900,000	41,900,000	
11	glycerin	150 gal/day, 5 days/week	339,000	409,000	
11 substrate sources			**133,300,000**	**173,500,000**	**6,500,000**

*Bold denotes samples in Biological Methane Potential test. Substrate 11 was identified further along in the project; data was provided by substrate generator.

Community biomass sampling report, 7/15/2009

In order to quantify the biomethane production potential of available non-farm waste streams in Lowville, samples were collected from willing providers within the town limits. All samples were kept in closed, plastic 1L containers and stored in a cooler filled with ice.

Around 9:00am the first sample was taken from substrate provider 7, a local family's residence. The sample from the home consisted of residential food waste, chopped with a knife and mixed using a food processor (Fig. 1).

Figure 2: Food waste from substrate provider 7.

While there are considerable logistical problems with getting a single sample that can be considered representative for residential food waste (which varies considerably in content and volume throughout the year and home by home), a sample of substrate 7 was taken in the hope that it might contribute to the formation of such a sample in the future.

Next, samples were taken from substrate provider 4. The offal was deposited in no particular order into eight oil drums and included blood, intestines, hides, livers, fat and other assorted butcher waste (Fig. 2). To make a sample as representative as possible, some blood was pooled into the container along with slices of liver, intestine and fat that had been mixed using a power drill. Since the waste was not uniform throughout or across the barrels, the sample incorporates elements from several of the barrels. However, caution should be taken in assuming that the sample is truly representative of what may be available on any given day throughout the year. The owner of the establishment noted that during deer season (October-December), deer bones would be the sole output.

Figure 3: Offal from substrate provider 4.

A sample was then taken from substrate provider 8. Employees explained that whey waste was emptied every day while the other waste product, CIP waste water, was emptied about every three days. Thus, a representative sample was taken by mixing three parts whey waste to one part CIP waste water. It should be noted that substrate provider 8 already pumps this waste outside to be trucked off-site; therefore, no infrastructure development would likely be necessary for the proposed digester project.

A local grocery store was unable to provide a sample, since the portion of their usable food waste not already donated to the local soup kitchen is deposited into a catch-all dumpster that also receives waste such as plastic, metal and other unusable refuse. Produce waste was piped through the local sewer system to the wastewater treatment plant after going through a garbage disposal. Collaboration between the bakery, produce, and meat departments also needs to improve in order to coordinate a large-scale waste separation process in the future.

Samples were then taken from 3 restaurants: substrate providers 9 and 5 (both 5A and 5B). All three contributed samples of mixed pre- and post- consumer food waste in addition to samples of fry grease. For the purpose of BMP trials, waste from substrate provider 9 is a mix of waste from two restaurants combined in proportion to the restaurant's contributions of both grease and food waste.

Similar samples were provided by substrate providers 2 and 3, albeit consisting of less grease than in the case of the restaurants. Substrate provider 2 was separating its waste by liquid and solid (both of which are included in the sample), but did not provide fry grease, while substrate provider 3 did.

Finally, a sample was taken from substrate provider 6 consisting of refuse flower stems, flowers, petals, and other plant matter.